

# Modelling the Photoresponse Characteristics of InP/InGaAs Heterojunction Phototransistor with Different incident Directions of Beam Light

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## Abstract

Numerical simulations of Heterojunction bipolar Phototransistor (HPT) were performed using a two-dimensional finite element program. These simulations are done on configurations of phototransistors which are realised in CNET Bagneux. Comparison between simulation and measurement was done for topside illumination and good agreement was found. Different incident directions of beam light were simulated to study their effects on frequency response of the phototransistor. For the configurations of transistor used in our work, it is found that the lateral illumination gives a better optical cut off frequency than the upside and the downside illuminations (72 GHz and 42 GHz respectively) for the same incident optical power.

## 1. Introduction

Thanks to the excellent electrical properties of InGaAs and InP, the InP/InGaAs HBT offers very good dc and microwave performances[1] [2] [3]. In this paper, we will investigate the optoelectronics possibilities of this structure in different types of illumination. The source of modulated light can be applied from the topside of the transistor or on its sides. But, due to the particular configuration of the InP/InGaAs transistor, it is also possible to apply the source light underneath. All these configurations were simulated using a two dimensional finite element simulator Atlas from Silvaco. This work is done in co-operation with CNET Bagneux which realises the structure of this HPT[2] [4]. The objective of this work is to prospect the performances of this structure using different directions of illumination of the device, and gain a better understanding of the physical phenomena acting in the HPT by building virtual experiments using the simulator program.

## 2. Models

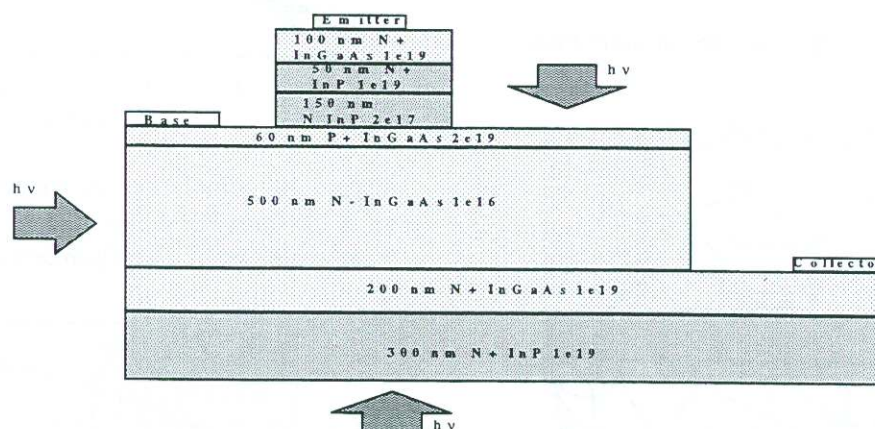


Figure 1 : HPT structure used in simulation. The arrows show the different ways of illuminations

The HPT uses the same epitaxial layer as an HBT as summarised in figure 1. The only difference is in the electrode structure which permits topside illumination. The fabrication process was detailed in [2]. In this figure, we also present the different ways of illumination of the HPT.

The simulations were done using ATLAS simulator from SILVACO. Basic equations to be solved are the Poisson's equation, continuity equations and current equations for electrons and holes. An enhanced drift diffusion numerical model which permits to take into account non uniform band structure of the base emitter



heterojunction is used by the simulator. The influence of carrier degeneracy based on Fermi-Dirac statistics is included in the band parameters.

The three main recombination processes are taken into consideration in this study : the Shockley-Read-Hall (SRH), Auger, and radiative recombination. Carriers lifetimes in SRH recombination are concentration dependent. Field dependent and concentration dependent mobilities were taken using analytical relationships for InGaAs and InP.

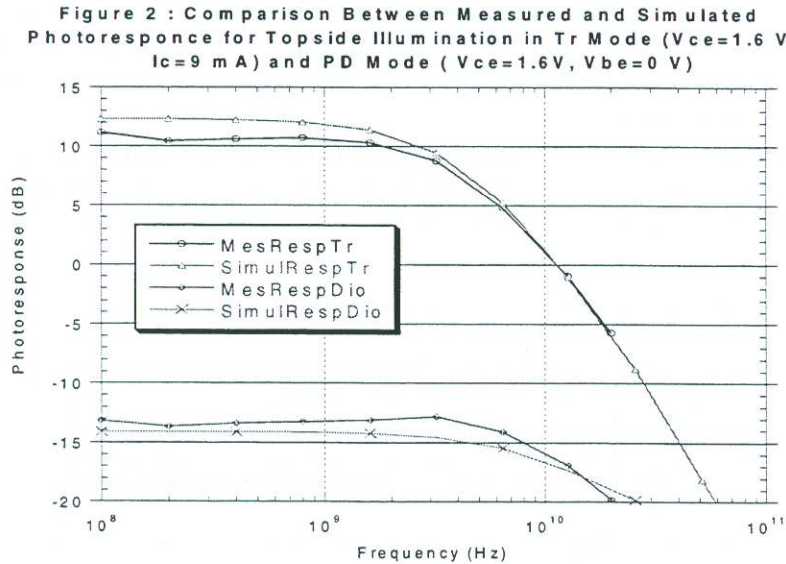
The optical generation rate of carriers is taken into account to simulate the interaction between light and semiconductor. It is given by :

$$G = \eta_0 \frac{P\lambda}{hc} \alpha \exp(-\alpha y)$$

where P contains the cumulative effects of reflections, transmissions, and losses due to absorption over the ray path,  $\eta_0$  is the internal quantum efficiency, h is Planck's constant,  $\lambda$  is the wavelength, c the velocity of light and  $\alpha$  is the absorption coefficient. The absorption coefficient used in our simulation is the same as in [5].

### 3. Frequency response of the HPT

Figure 2 shows the measured and simulated photoresponse of the HPT in dB. The wavelength of the optical signal was 1.55  $\mu\text{m}$  and its intensity was modulated by a RF signal ranging from 130 MHz to 20 GHz. The simulation is in good agreement with measurement in phototransistor mode operation (Tr-Mode) as well as photodiode mode operation (PD-Mode). Unit optical gain cut-off frequency  $f_c$  defined as the cross point between PD-Mode responsivity at low frequency and the extrapolation of TR-Mode responsivity. Simulation and measurement give the same  $f_c$  of 42 GHz.

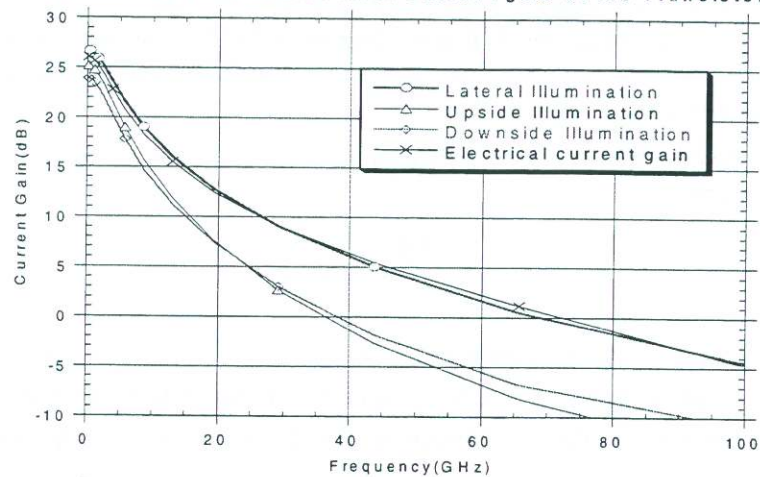


Simulations were done to study the frequency performance of the phototransistor for different directions of illumination. Figure 3 shows the optical current gain vs frequency. Phototransistor mode (PT-Mode) was used with a constant current condition of  $I_b=400\text{ }\mu\text{A}$  in base electrode and  $V_{ce}=1.6\text{ V}$ . The optical current gain  $g$  is defined as :

$$g = I_c/I_{ph}$$

$I_c$  is the collector current and  $I_{ph}$  the available photo current generated by the incident light.

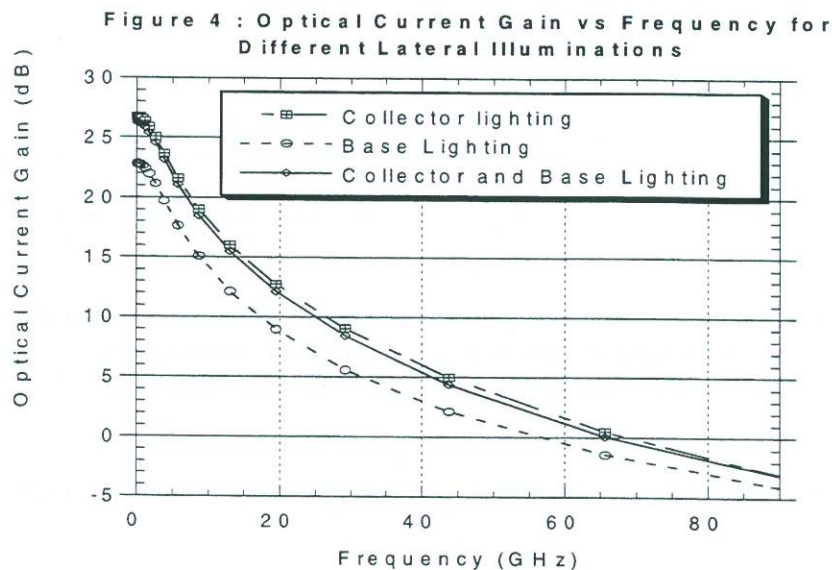
Figure 3 : Optical Current Gain vs Frequency for Different Directions of Illumination Compared to Common Emitter Electrical Current gain of the Transistor



The optical cut-off frequency is defined as the frequency at which the optical current gain is equal to 0 dB. We observed, that the lateral illumination gives a better frequency performance and a higher current gain than for the upside and downside illuminations ( $f_c=72$  GHz for lateral illumination, and 42 GHz for upside and downside illuminations). The best frequency performance of lateral illumination is due to the fact that all photogeneration of carriers was done in a depleted region of the collector where the carriers are rapidly swept, while in the upside and downside illuminations, some of the photogenerated carriers are created in neutral regions (base layer, sub collector layer and a small part of the collector layer). These photocarriers, which were in excess, increase the charge stored by the device which increases the total junction capacitance and then decrease cut-off frequency.

The difference in current gain is due to the recombination of photogenerated carriers in the neutral zone of base and sub collector for the upside and downside illuminations. This phenomenon is not observed when only the collector layer is lightened, because we have a strong electrical field which separates electrons and holes and sweeps them to the base for the holes, and collector for the electrons. When we compared this curves with the electrical performance of the HPT, we observed that the best optical results are very close but never exceed the electrical current gain.

To study the effect of the generated part of carriers in neutral zone of the device, we perform three different simulations where we illuminate separately the base layer, the collector layer and finally both layers. The frequency response is shown in figure 4 and the lightened areas are shown in figure 5.



As expected, the best result is given when the light illuminates only a depleted region of the collector ( $f_c=72$  GHz and  $g=26$  dB). When only the base layer is lightened, the cut-off frequency falls down to 58 GHz and



the current gain to 23. The base and collector layers are also lightened together. The frequency performance is slightly above the case where only the collector is illuminated, because a small part of the photogenerated light is in the neutral region of the base layer.

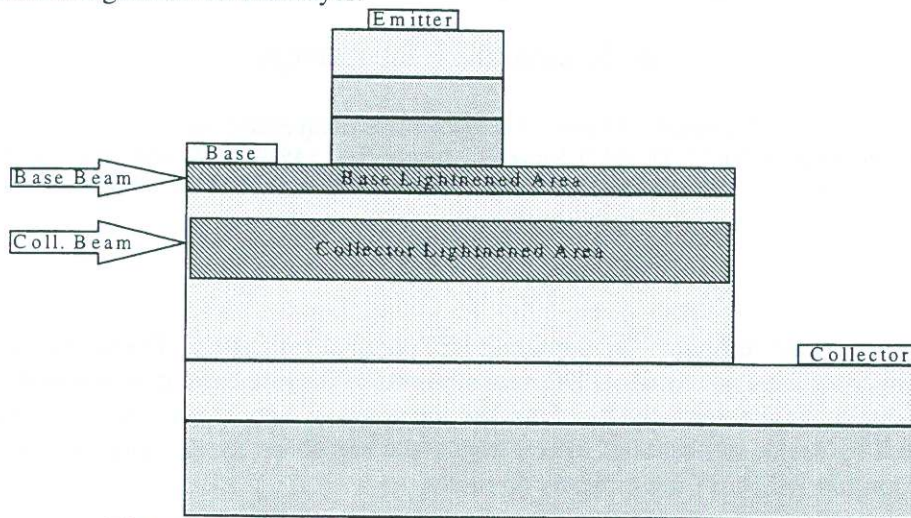


Figure 5 : Different lightened areas used in lateral Illumination

#### 4. Conclusion

Different incident lights were applied to HPT to study its frequency performances. It was shown that the best way to illuminate the device is the lateral illumination. But, due to the small thickness of the vertical dimension of the HPT ( $0.8 \mu\text{m}$ ) it will be very difficult to illuminate the device on its sides. Nevertheless, this study gives us insights into the effect of the photogenerated carriers in the different layers of the device. We have shown that all the carriers photogenerated in the depleted region are used in the optical gain of the HPT without any decreasing in the frequency performance. The carriers generated in the neutral regions of the device suffer from the recombination process and then decrease the optical gain and the cut-off frequency.

#### References

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